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Procedia Engineering 15 (2011) 2762 – 2766

Procedia Engineering

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Advanced in Control Engineering and Information Science

# Dexterous space optimization for robotic belt grinding

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**Abstract**

Industrial robots are recently introduced to the belt grinding of complex shaped surfaces to obtain high productive efficiency and constant surface quality. The volume of dexterous grinding workspace is a key factor the grinding robot, in which the gripped workpiece could obtain continuous grinding path and constant surface quality. This paper proposes a new structure of a robotic grinding system in which a new robot frame including active work piece frame {W} and passive tool frame {T} was presented. It shows that the dexterity of the system, which is indexed by the volume of dexterous workspace, is affected by the position of the contact wheel relative to the robot. Based on pattern search method, a strategy to optimize the grinding robot position with respect to the grinding wheel is put forward to obtain the desired dexterity grinding space.



Selection and/or peer-review under responsibility of [CEIS 2011]

Keywords: robot; kinematics; dexterity; optimization; Pattern search method

## 1. Introductions

The early development of robotic grinding focused on the robot holding a grinding wheel to finish a part with simply geometries and with relatively low accuracy requirements [1]. It is quickly accepted by the work force particularly since it also improves working conditions and does not require extra remedial work before and after. Belt grinding system replaces the earlier active tool grinding way, which is widely used in the robotic grinding system. The topological structure of a moving workpiece clamped at the end-effector and a fixed tool, which is more popular because it has better scalability and more possibilities to optimize. By integrating multi-degree industrial robot as manipulator, a flexible manufacturing cell can be formed, which is especially suitable for processing surfaces with complicate geometry like turbine blades or faucets. A typical robotic belt grinding system is composed of an industrial manipulator, a belt grinder


doi:10.1016/j.proeng.2011.08.520

and the workpiece[2]. This system is designed to finish the work piece with complex surface, such as aero-engine blades, water turbine blades, high-grade furniture and artificial limbs. In general, their working process is as follows: The end-effector of the robot grips the workpiece, which is delivered to the belt grinding grinder. As the workpiece approaching to contact wheel, the surface of the workpiece is shaped by the abrasive belt.Many scholars have researched in the manipulator dexterity[3-4]. The dexterity space is described by the service sphere and service zone which is based on the moving tool at the end effector and a fixed workpiece and an active tool-positive workpiece coordinate system was established. But in the robotic belt grinding system, the workpiece is moving and the tool-grinding wheel is fixed, thus the methods above-mentioned is not suitable for grinding robot system.

In summary, the dexterity optimization aims are as follows: first, the establishment of an appropriate coordinate system for the general theoretical analysis; second, the robot placed in a reasonable relative position to grinding machine ensuring that the robot has enough dexterous space for grinding.

## 2. Structure and kinematics analysis of grinding robot

Cartesian-coordinate is adopted in the hand of grinding robot. The wrist has 3R manipulators with orthogonal joint axes, and any joint has full 360-degree motion. As shown in Fig.1, the robot is a PPPRRR structure. Joint Z1,Z2,Z3 are Cartesian Coordinate prismatic, which respectively make the end-effector move forward-back, left-right, up-down. Joint Z4, Z5, Z6 are revolute, by which the end-effector change orientation and the workpiece is clamped at the end-effector.

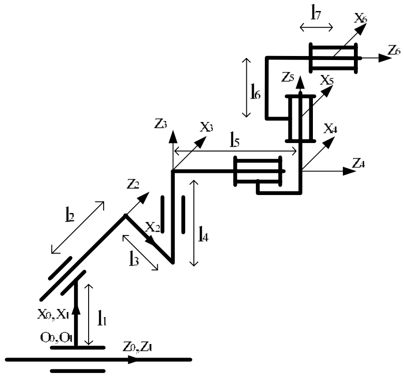



Fig.1 Mechanism simple figure of grinding robot

The forward kinematics expresses the orientation of the end-effector {6} in Frame {O}. Using the D-H notation along with the D-H parameters, the generalized rotation matrix is defined as follows:

$$
{}^0_6T = {}^0_1T\,{}^1_2T\,{}^2_3T\,{}^3_4T\,{}^4_5T\,{}^5_6T = \begin{bmatrix} s_4c_5c_6 + c_4s_6 & -s_4c_5s_6 + c_4c_6 & s_4s_5 & l_7s_4s_5 + l_6c_4 + l_1 + d_3 \\ -c_4c_5c_6 + s_4s_6 & c_4c_5s_6 + s_4c_6 & -c_4s_5 & -l_7c_4s_5 + l_6s_4 - d_2 \\ -s_5c_6 & s_5s_6 & c_5 & l_7c_5 + d_1 + l_3 + l_5 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)
$$

In equation (1), $s_i = sin\theta_i$, $c_i = cos\theta_i$.

## 3. Analysis and optimization for dexterous grinding space

Dexterous workspace is that volume of space that the robot end-effector of the manipulator can reach with all orientations. That is, at each point in the dexterous workspace, the end-effector can be arbitrarily oriented [5]. In the traditional robot system, the robot holds the tool and works on a fixed work piece. Otherwise, in the robotic grinding system it is inverse that the work piece is actively moving and the tool is passively fixed. There are three definitions in paper [5], and this paper will analyze the dexterity of the grinding robot on the base of the first definition.As shown in Fig.2, 1 is the grinding robot, 2 is the workpiece,3 is the grinding wheel; {O} is the robot base frame, {6} is the wrist frame, {T} is the tool frame, {W} is the workpiece frame. Considering the relations between the frames, a transform equation leads to:

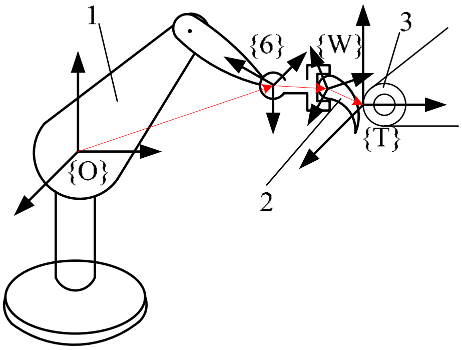



Fig 2. Relations between frames of the robotic system

Fig.3 Robotic grinding system

$$ {}^{0}_{6}\boldsymbol{T} = {}^{0}_{T}\boldsymbol{T} \cdot \left( {}^{6}_{W}\boldsymbol{T} \right)^{-1} \tag{2} $$

The tool frame {T} relative to base frame {O} is described

$$ {}^{0}_{T}\boldsymbol{T} = \begin{bmatrix} 1 & 0 & 0 & x \\ 0 & 1 & 0 & y \\ 0 & 0 & 1 & z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3} $$

Adopting a point somewhere on the surface of the work piece, we assume its position ($P_x$, $P_y$, $P_z$), and the rotation angle α, β, γ. On the base of Z-Y-Z Euler angles, calculate the frame {W} relative to {O} as

$$ {}^{0}_{W}\boldsymbol{T} = \begin{bmatrix} c\alpha c\beta c\gamma - s\alpha s\gamma & -s\alpha c\gamma - c\alpha c\beta s\gamma & c\alpha s\beta & Px \\ s\alpha c\beta c\gamma + c\alpha s\gamma & c\alpha c\gamma - s\alpha c\beta s\gamma & s\alpha s\beta & Py \\ -s\beta c\gamma & s\beta s\gamma & c\beta & Pz \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4} $$

According to (2), (3) and (4), we obtain that: $\alpha=\pi-\theta_6$， $\beta=\theta_5$， $\gamma=3\pi/2-\theta_4$.Obviously，there is a one-to-one relationship between the rotational joints $\theta_4$, $\theta_5$, $\theta_6$ of the robot and γ, β, α, and it also prove that three orthogonal wrist can attain general goal position and orientations [6].The grinding point on the surface of the work piece and the origin of {T} coincide：

$$ \left. \begin{aligned} d_1 &= z - P_z c\beta - P_x c\alpha s\beta - P_y s\alpha s\beta - l_3 - l_5 \\ d_2 &= y + l_6 s\theta_4 - P_x(s\alpha c\gamma + c\alpha c\beta s\gamma) + P_y(c\alpha c\gamma - s\alpha c\beta s\gamma) + P_z s\beta s\gamma \\ d_3 &= x - P_Z c\gamma c\beta - P_y(s\alpha c\beta c\gamma + c\alpha s\gamma) - P_x(c\alpha c\beta c\gamma - s\alpha s\gamma) - l_6 c\theta_4 - l_1 \end{aligned} \right\} \tag{5} $$

Regarding $d_1$, $d_2$, $d_3$ as variables， equation（5）can be expressed as：

$$\left.\begin{aligned} d_1 &= f_1(\theta_4,\theta_5,\theta_6,P_x,P_y,P_z,x,y,z,l_1,l_2,l_3,l_4,l_5,l_6) \\ d_2 &= f_2(\theta_4,\theta_5,\theta_6,P_x,P_y,P_z,x,y,z,l_1,l_2,l_3,l_4,l_5,l_6) \\ d_3 &= f_3(\theta_4,\theta_5,\theta_6,P_x,P_y,P_z,x,y,z,l_1,l_2,l_3,l_4,l_5,l_6) \end{aligned}\right\} \quad (6)$$

If the parameters of the robot and the position ($x$, $y$, $z$) of {T} relative to {O} are certain, adopting a point somewhere from the surface of the work piece, whose position ($P_x$, $Py$, $P_z$), we can attain equation (7),which describe the relation between $d_1$,$d_2$,$d_3$ and $\theta_4$, $\theta_5$, $\theta_6$.

$$d = f(\theta_4,\theta_5,\theta_6) \quad (7)$$

Traversing $\theta_4$, $\theta_5$, $\theta_6$ in their 360-degree motion, then we can attain $d_1$,$d_2$,$d_3$.

$$d_{\min} < f(\theta_4,\theta_5,\theta_6) < d_{\max} \quad (8)$$

Analysis on the dexterous grinding point $P$=($P_x$, $Py$, $P_z$) in space, we need to traverse $\theta_4$, $\theta_5$, $\theta_6$ in their 360-degree motion, and derive the $d_1$,$d_2$,$d_3$.If $d_1$,$d_2$,$d_3$ meet equation (8), it proves that the position and orientations could be realized. So we regard it as a dexterous grinding point; otherwise, not dexterous grinding point. Calculation for the dexterous space, check all the points in the target space one by one, and accumulate all the dexterous points. There are more dexterous grinding points; the dexterity of space is greater.

Because of irregular size and sharp curvature variations of the workpiece, the robot should not only have enough dexterous workspace that the normal direction of grinding point on the workpiece surface and the contact wheel should coincide, but also make sure that the grinding path is continuous during manufacturing so that the workpiece can be finished in one path. However, in the actual grinding process, the robot's joints are usually beyond distance limits in the planned path, which result in the discontinuous grinding path and affected machining precision. By analyzing the result, it shows that one of the important reasons is the illogical relative position between the robot and the contact wheel.

From equation (5) and (6), three prismatic joints position $d_1$, $d_2$, $d_3$ and the relative position between the robot and the contact wheel $x, y, z$ are coupled. The volume and distribution of the dexterous space is closely related to the relative position between {T} and {O}. So the task of dexterity optimization is to find out a perfect relative position where the dexterous space at end-effector of the manipulator is largest.

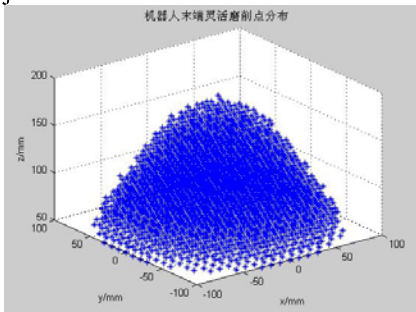
## 4. Pattern search method

Hooker and Jeeves proposed Pattern search method [7], whose basic idea is: Starting from a mountain somewhere, trying to come to a basin near the lowest point, if you can find a valley, along the valley road is the most efficient way. A trial step $s^i_k$ is defined by $s^l_k = \Delta k p^l_k$, where $\Delta_k$ is a constant which determines the length of the search step and $p^l_k$ is the $i^{th}$ column in the matrix $P_k$. The $i^{th}$ trial point in the pattern is given by $q^l_k = q_k + s^l_k$. The specific algorithm is as follows:

1. Given $\Delta_k$ and $\tau$, randomly pick an initial center of pattern $q_k$, then compute the function value $f(q_k)$, and set min←$f(q_k)$.
2. If $\Delta_k \leqslant \tau$ then stop.
3. For i = 1, ……, p − 1 where p is number of columns in $P_k$.
4. $q^i_k \leftarrow q_k + s^i_k$.
5. Compute $f(q^i_k)$
6. If $f(q^i_k)$<min, then
7. $q_{k+1} \leftarrow q_i$ ; $\Delta_{k+1} \leftarrow \Delta_k$ ;min←$f(q^i_k)$;k←k+1..
8. $\Delta_{k+1} \leftarrow \Delta_k/2$;k←k+1; go to 2.

Take the position of tool frame {T} relative to base frame {O} x, y, and z as the variables. Initial centre of pattern $q^1_k$ =[x y z]=[475 20 540],dimension of optimal vector n=3, initial step $s_k$=50, $s^i_k$ =5,the targetfunction $f(q^i_k)$ is the opposite number for the sum of all the dexterous points.

Fig.3 shows the robotic grinding system. The robot parameters (mm): $l_1$ =220; $l_2$ =0; $l_3$ =230; $l_5$ =350; $l_6$ =120; $l_7$ =0. Limit of joints： $-225 \le d_1 \le 225$; $-225 \le d_2 \le 225$; $0 \le d_3 \le 500$; $0 \le \theta_4 \le 2\pi$; $-\pi \le \theta_5 \le \pi$; $\pi/2 \le \theta_6 \le 5\pi/2$.We traverse the points one by one in the clamping space at the end-effector of the robot. Step of $P_x$ , $P_y$ ,$P_z$ and $\theta_4$, $\theta_5$ , $\theta_6$ are 10mm and $\pi/20$. Using equation (8) to judge whether the target point is dexterous or not and accumulate all the dexterous points. The results are shown that when {T} position relative to {O} is (475,0,580), the dexterous points are most. Fig.4（a） shows that the dexterous space is almost half a sphere whose volume is 2088100mm$^3$. Fig.4（b） shows the cross section of the sphere at 6th joint z=50. Contrast to the result before optimization, the dexterous space has been doubled.



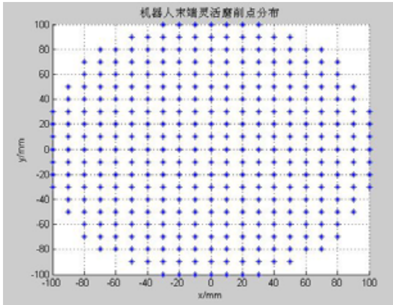




Fig.4. (a) Grinding point after optimizing; (b) Cross section z=50 of the dexterity space

## 5. Conclusion

This paper points out the difference on the working mode between grinding robot and normal one. A new robot frame including active work piece frame {W} and passive tool frame {T} was presented, which provides theory basis for the analysis of grinding robot dexterity. In the robotic grinding system, the dexterity space is defined at the end-effector. It is presented that the relative position (x, y, z) between the base frame of the robot {O} and {T} was a key factor impacted on dexterous workspace of the grinding robot which are taken as the factors for Pattern search method. We can conclude that for a certain workpiece, when the relative position is (475, 0, 580), the dexterity space reach the maximum.

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